# The Detection and Study of Pre-Planetary Disks

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**Abstract.**
A variety of evidence suggests that at least 50% of low-mass stars are surrounded by disks of the gas and dust similar to the nebula that surrounded the Sun, before the formation of the planets. The properties of these disks may bear strongly 011 the way in which planetary systems form and evolve. As a result of major instrumental developments over the last decade, it is now possible to detect and study the circumstellar environments of very young, solar-type stars in some detail, and to compare the results with theoretical models of the early solar system. For example, milli]r)ctet-wave aperture synthesis imaging provides a direct means of studying in detail the morphology, temperature and density distributions, velocity field and chemical constituents in the outer disks, while high resolution, near infrared spectroscopy probes the inner, warmer parts; the emergence of gaps in the disks, possibly reflecting the formation of planets, may be reflected in the variation of their dust continuum emission with wavelength. We review progress to date and discuss likely directions for future research.

**Key words:** disks-circumstellar, disks-pre-planetary, ]nrn-wave interferometry

## 1 Introduction

Stars like the sun form in dense, $10^5$ - $10^7$ c m$^{-3}$, cool, 10 - 35 **K** concentrations in interstellar molecular clouds (e.g. Benson & Myers 1989; Myers & Fuller 1992). These slowly rotating cores, initially ranging in size from thousands of AU to tenths of a parsec, become gravitationally unstable and collapse to produce a central condensation a proto-star surrounded by an accretion disk, and embedded in an envelope of still-infalling gas arId dust (*cf* **Shu** *et al.* 1987; 1993). over a period of about 105 years, the proto-stellar core gradually increases in mass and a strong wind develops, breaking through the envelope at the rotational poles of the star-disk system in two oppositely-directed outflows. Ensuing dissipation of the obscuring material results in the emergence of a visible star with a circumstellar disk. Current theories of solar system formation suggest that the formation of planetesimals and eventually planets took place in such a disk (*cf* Safronov 1991).

As a result of recent instrumental advances, the circumstellar disks still associated with very young stars earl now be observed, Many appear similar to the pre-solar nebula, the disk of gas and dust that surrounded the sun in its infancy, 4.5 x $10^9$ years ago, and from which the planets formed (*cf* Lin & Papaloizou 1985; Safronov 1991). Studies of these pre-planetary disks may therefore supply clues to how the present solar system evolved. In addition, they provide a method of establishing how often other planetary systems occur. For the present, this cannot be determined by searching for mature planetary systems since many factors, notably the small surface area of planets and the enormous contrast in brightness between them and their central stars, prevent direct observation of planets around other stars.

## 2 Detecting Disks

We can estimate the properties of proto-planetary disks by extrapolating from the present solar system. Theory suggests that the mass of the young solar nebula was at least $0.01 M_{\odot}$ (Lin & Papaloizou 1985; Safronov 1991). Co-planarity and co-revolution of the planets imply a highly-flattened disk with diameter of order 100 AU, the approximate diameter of Pluto's orbit. The velocity field should be Keplerian, of the form $v \propto r^{-0.5}$. Expected disk surface temperatures at about 1 AU from a young, solar-type star cab be 110 more than a few x 100 K, decreasing with increasing radius to a few x 10 K. Disk observations are therefore best undertaken at the infrared arid millimeter wavelengths where relatively cool dust grains preferentially emit. Spectra] line emission from a wide variety of molecular species is also found at millimeter wavelengths, allowing important analyses of disk velocity structure.

our understanding of pre-planetary disks has benefited enormously from technological developments over the last decade that have improved spectral and spatial resolution, as well as sensitivity in the infrared and millimeter- wave bands. Observations with the infrared Astronomical Satellite (IRAS), launched in 1983 to survey the entire sky at wavelengths of 12, 25, 60 and 100 $\mu m$, have had a major impact. The high-sensitivity IRAS measurements demonstrated that as many as 30% of nearby A stars, including Vega, emit considerably more infrared radiation than is expected from the stellar photosphere alone (Aumann *et al.* 1984; Gillett 1986; Backman & Gillett 1987). Although these stars are almost as old as the Sun, typically a few x $10^8$ years, the "Vega phenomenon" is attributed to orbiting dust particles; optical corona-graph observations of one such object, $\beta$ Pictoris, reveal that the dust lies in an edge-on disk with radius many hundreds of AU (Smith & Terrile 1984). The considerable body of observational data that now exists suggests that $10^{-5} M_{\odot}$ disks, perhaps the residue of planet formation, surround Vega-type stars (*cf* Becklin & Zuckerman 1990; Lagrange-Henri et al. 1990; Telesco & Knacke 1991; Boggess *et al.* 1991; Chini *et* al. 1991; Backman & Paresce 1993).

The IRAS observations of very young ($3 \times 10^5$ to $3 \times 10^7$ years) solar-mass stars also show excess infrared emission that can be attributed to circumstellar disks (Adams *et al.* 1987; 1988; Strom *et al.* 1989). Many other features peculiar to these T Tauri stars, including enhanced infrared and ultraviolet fluxes, asymmetric emission line profiles, optical jets and bipolar molecular outflows, are also readily explained if disks of radius $\sim$a few x 100 AU are present (*cf* Appenzeller &

Mundt 1989; Bertout 1989; Edwards *et al.* 1993). In the nearest star-forming clouds, at 140 pc distance, 100 AU corresponds to 0.7". Confirmation of disk morphology and detailed investigations of disk properties therefore require imaging at arcsecond spatial resolution. Gross properties can, however, be derived by comparing lower resolution observations of the near-infrared to millimeter-wave dust continuum emission with those expected for star-disk systems (see Beckwith & Sargent 1993a, and references therein). Using this technique, large numbers of stars can be searched quite rapidly for the dust continuum radiation typical of disks. Spectral energy distributions (SED's) based on IRAS flux measurements (Strom *et al.* 1989) and IRAM 30-meter telescope observations at wavelength $\lambda =$ 1.3 mm (Beckwith *et al.* 1990), imply that disks surround at least 50% of nearby T Tauri stars.

At wavelengths shortward of 100 pin, the dust emission is optically thick and the SED's give the disk radial temperature distributions, $T_0(r/r_0)^{-q}$; optically thin emission at sub-millimeter and millimeter wavelengths is sensitive to the disk mass, $M_d$. Beckwith *et al.* (1990) derive disk temperatures between 50 and 400 K at 1 AU from the star; the power law index of the temperature distribution, q, is between 0.5 and 0.75; outer radii are typically a few x 100 AU; masses, $M_d$, are between 0.003 and 3 $M_{\odot}$. These parameters are consistent with the presence of pre-planetary disks. Adams *et al.* (1990) obtain higher values of $M_d$ for a smaller sample of T Tauri stars, using a lower adopted value of $\kappa_\nu$, the mass opacity coefficient. Adopted values for $\kappa_\nu$ vary widely *cf* Beckwith & Sargent 1991); within the uncertainties, $M_d$ is in most cases greater than required to form the minimum mass solar nebula. These pre-planetary disks are very different from the 'debris' disks that surround the older, Vega-type stars; masses, for example, are orders of magnitude higher. Evolution between these extremes should, in principle, reflect the evolution Of the solar system.

## 3 Investigating Disk Properties

nigh resolution millimeter-wavelength line and continuum observations can directly confirm the disk morphology inferred from low resolution surveys and establish if the gas is moving in Keplerian orbits, as would be expected for a reservoir of material from which planets form. If the disks are indeed proto-planetary in nature, more detailed studies of their physical and chemical characteristics are required for comparison with models of planetary system formation and evolution.

Millimeter-wave interferometers that can provide the required resolution began operation in the 1980's, and disk-like structures around a few very young objects have been mapped (Beckwith *et al.* 1986; Mundy *et al.* 1986; 1992; Sargent & Beckwith 1987: 1991; Weintraub, Masson & Zuckerman 1989; Sargent *et al.* 1989; Walker *et al.* 1990; Ohashi *et al.* 1991; Simon & Guilloteau 1992; Kawabe *et* al. 1993; Koerner *et al.* 1993a; 1993b; Sargent & Beckwith 1993). Figures 1a and 1b are 2.7" resolution images of the low velocity $^{13}CO(1\rightarrow0)$ emission from the

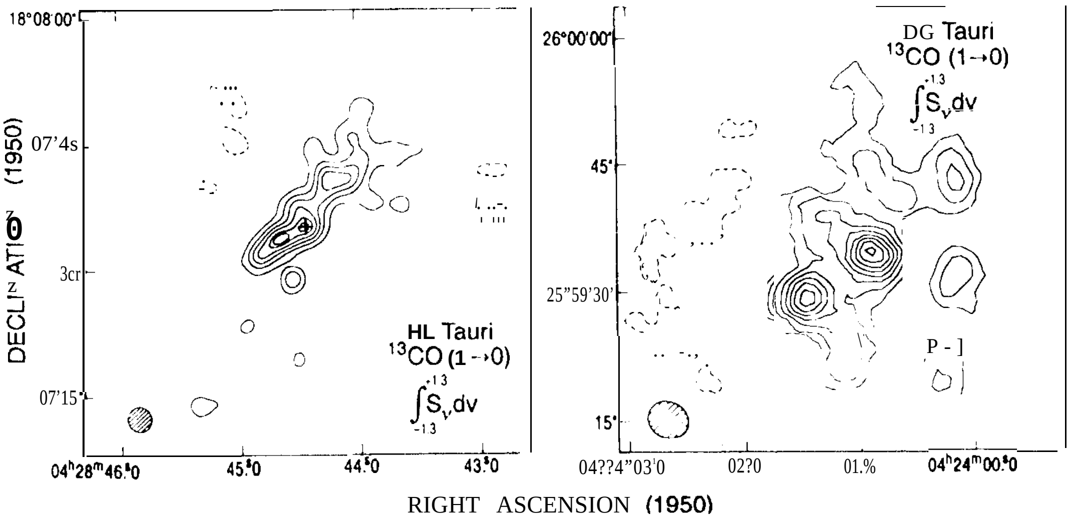


Fig. 1. Maps of the distributions of low-velocity ($v_{sys} \pm 1.3$ km S-l), $^{13}$CO$(1 \rightarrow 0)$ emission around a) HL Tauri and b) DG Tauri. In each map a cross represents the position of the star. Contours begin at 60 mJy $(2\sigma)$ and are spaced by 30 mJy. In maps that include contributions from the higher velocity gas, emission is unresolved and concentrated within the highest central contours shown above.

"1' Tauri stars HL Tauri and DG Tauri. For velocities, v(systemic) $\pm$ 1.3 km s-l, both show elongated gaseous structures extending to radii of almost 2000 AU. in each case, high velocity gas, and also the $\lambda$ = 2.7 mm dust continuum emission, is confined to an unresolved core, $\leq$ 200 AU in radius, centered on the star, Disk masses calculated from the $^{13}$CO fluxes are $\sim 0.1 M_{\odot}$, for HI, 'i'au, and 0.04- to 0.05 $M_{\odot}$, for DG Tau, in good agreement with the values derived in the IRAM survey of 1.3 mm dust continuum emission (Beckwith et al. 1990). Stellar ages are a few x $10^5$ years, as anticipated for stars supporting pre-p]anetary systems.

To date, evidence for Keplerian velocity structure in the disks associated with young stars is compelling but not unambiguous. A simple analysis of the velocity pattern in HL Tau suggests a circumstellar disk of gas is in Keplerian rotation about the star (Sargent & Beckwith 1987; 1991). Studies of the velocity structure in DG Tau are not yet complete, but the fact that high velocity gas is concentrated in a core while the low velocity material is extended as shown in Figure lb, is consistent with gas in Keplerian orbits (Sargent & Beckwith 1993).

A persistent problem is caused by contributions to the CO and $^{13}$CO emission from the ambient clouds in which most of the 'J' Tauri stars are found. Large-scale cloud structure ($\geq$ 15") is resolved out by the milli meter-wave interferometers, but smaller-scale features in the inhomogeneous cloud are detected as a result of the enhanced sensitivity. This makes it difficult to completely isolate the velocity structure of any disks. Aperture synthesis observations of molecular species that trace only denser gas should, in principle, alleviate the problem. The lower rotational transitions of CO are excited at densities an order of magnitude lower than required to produce CS ($2 \rightarrow 1$) emission. Imaging of the dense disks in the millimeter-wave spectral lines of the CS molecule should therefore discriminate against more diffuse ambient cloud features.

Interferometric CS (2+1) observations of H], and DG Tau are reported by Ohashi et al. (1991), 'l'he CS ($2 \rightarrow 1$) emission around HL Tau has also been mapped by Blake *et al.* (1992). Extended structures with radii 2000 AU are observed, but in neither case is the gas centered 011 the stars; the displacements, ~ 3 - 5", are significant. Imaging of the proto-type of the class, T Tauri, also indicates a dearth of CS ($2 \rightarrow 1$) molecular line emission at the stellar position (van Langevelde *et al.* 1993). From excitation calculations that incorporate the results of **IRAM** searches for emission in higher rotational CS transitions, Blake *et al.* (1992) infer molecular hydrogen densities of $10^4$ - 105 cm$^{-3}$, and CS fractional abundances $\sim 10^{-8}$ for the gas around HL Tau. These values are typical for standard cloud cores in the Taurus region and imply that the CS observations are probing an outer envelope rather than the circumstellar disk. The models imply that CS is depleted by factors of 25 - 50 in the disk itself. An attractive possibility is that gas-phase CS is converted into other sulfur-bearing molecules, as in the inner part of the proto-solar nebula, (Barshay & Lewis 1976).

Modeling the millimeter-wave molecular line emission expected from proto-planetary disks for comparison with aperture synthesis observations of circumstellar gas is likely to be most effective method of establishing the disk velocity fields. Calculations of the $^{13}$CO ($1 \rightarrow 0$) emission expected from a rotating disk have recently been carried out by Beckwith & Sargent (1993b). A comparison of synthetic aperture synthesis maps based on these calculations with $^{13}$CO images of the T Tauri star, GM Auriga, show' very good agreement (Koerner *et al.* 1993). It appears that a proto-planetary disk of mass 0.08 $M_{\odot}$ and radius $\sim$ 200 AU orbits this 0.7 $M_{\odot}$ star, although higher spatial and spectra] resolution maps are needed to remove all uncertainties from this interpretation.

Somewhat unexpectedly, the disk calculation of Beckwith & Sargent (1993) demonstrate that not only CO ($1 \rightarrow 0$) but also $^{13}$CO ($1 \rightarrow 0$) emission is optically thick for disk masses $\geq$ 0.001 $M_{\odot}$. This suggests that CO and $^{13}$CO interferometric observations to date have reflected only disk temperature distributions ant] have provided 110 information about the density structure. Tracing the density variations in disks evidently requires observations in rarer isotopes, such as C$^{18}$O or C$^{17}$O, that are much less abundant, with optically thin emission. Preliminary

$HCO^+$ maps of T Tauri indicate that, unlike CS, this species may prove a reliable density tracer (van Langevelde *et al.* 1993).

Additional support for the presence of disks around very young stars is now being provided by observations of spectral line emission at near-infrared wavelengths. As described above, these observations probe the velocity field of the inner disk, close to the star. Echelle spectrographs capable of achieving the necessary high spectral resolution in this wavelength band have only recently begun operation. Model fits to observations of the 2.2$\mu$m CO band-head emission from WL16 by Chandler *et al.* (1993), for example, suggest an inner disk radius 0.04 AU. Similar observations of DG Tau by these authors are more complicated to model but also indicate the presence of a disk.

## 4 Disk Evolution

Changing disk properties between the pre-planetary and debris extremes discussed above should reflect the evolution of the solar system. In fact, there is no clear indication of diminution of total disk mass over the stellar age range spanned by the Beckwith *et al.* (1990) survey, $2 \times 10^5$ - to $3 \times 10^6$ years. However, unexpectedly low 12 and 25$\mu$ fluxes are noted for a number of stars and may indicate a form of evolution depletion of dust in the inner regions of the disks. Such "clearing" could, in turn, presage the onset of planetary formation (Skrutskie *et al.* 1989; Beckwith *et* al. 1990; Strom *et al.* 1993). Stars with inner holes tend to display other characteristics of disk evolution, such as decreased accretion activity in their disks (*cf* Edwards *et al.* 1993; Strom *et* al. 1993).

With age $2 \times 10^6$ years, GM Aurigae, mentioned above, is among the oldest T Tauri stars in the samples searched for disks. Although the mass of the disk remains substantial, 0.08 $M_\odot$, the SED for GM Aur suggests clearing of dust within 0.36 AU of the star and there is little evidence of accretion (Beckwith *et al.* 1990; Koerner *et* al. 1993). Small-scale deviations of the near infrared fluxes from those implied by filled-disk models have been interpreted as signifying the existence of gaps in the GM Aur disk, perhaps the effect of forming planets (Marsh & Mahoney 1992). Although depressed near and mid-infrared flux values can be explained by the combined effects of dust grain opacity ant] vertical structure in the disks (Hess & Yorke 1993), it seems likely that GM Aur is an example of a more evolved star-disk system.

Disk dissipation may also be affected by FU Orionis events. 'l'his phenomenon, a sudden brightening of a star by several magnitudes, with a subsequent decrease in visual intensity lasting for many years, is named for the object in which it was first observed (Herbig 1977). Many of the properties of FUors can be explained by model in which an accretion disk surrounds a '1' Tauri star; the outburst is correlated with dramatic increase in the disk accretion rate (Hartmann & Kenyon 1985). '1' Tauri stars may experience numerous FUor events in their early evolution, the disk material dissipating a little more with each outburst (*cf* Hartmann *et al.*

1993). It is not clear how this effect would impinge upon the formation of a planetary system, but it is notable that infrared and optical spectroscopic, studies of at least one FUor, V1057 Cyg, suggest Keplerian rotation (Hartmann & Kenyon 1987).

Further studies of FU Orionis objects are clearly in order. In addition, observations of disks around older stars, and of systems for which the SED's indicate less massive disks, are needed. These will extend studies of disk evolution and establish the evolutionary path of the early solar nebula.

## 5 The Future

With the launch of ESA's infrared Space observatory (ISO) and, in the more distant future, NASA's Space infrared Telescope Facility (SIRTF), infrared surveys of the type pioneered by IRAS will continue. The higher resolution and sensitivity compared to IRAS will allow the determination of more accurate continuum SED's for a much larger of sample of possible pre-planetary disks. A wide range of stellar ages aud masses will be encompassed by these surveys, Inevitably, these will increase the pool of objects for mapping and should greatly enhance our knowledge of disk evolution.

Very few disks have been imaged to date. Because each of the millimeter-wave interferometers began operation with only a few telescopes, mapping has been a laborious and time-consuming process. All the arrays are currently expanding and upgrading equipment, and the VLA is being modified for operation at $\lambda =$ 7 mm. As a result, interferometric surveys will be viable. These will enable the very sensitive searches for small-scale circumstellar material that are necessary to improve our understanding of disk dissipation, with obvious implications for solar system evolution. Such surveys will also clarify how many stars are likely to support forming solar systems.

The upgraded improved millimeter-wave arrays will also provide the very high spatial and spectra] resolution that are vital to detailed studies of disk properties. Analysis of the velocity structure of the cool, outer disks will be readily undertaken. Studies of various molecular species will allow studies of the temperature, density and chemical variations across these disks, In addition, studies of the inner, warm regions of pre-planetary disks will adavnce as spectra] resolution at infrared wavelengths continues to improve. It is antipated that the two Keck telescopes and the European Southern Observatory's Very Large Telescope will employ a number of small out-rigger telescopes to carry out infrared interferometry and enable imaging of these warm disks. In terms of detecting and studying pre-planetary disks, we are on the threshold of a new scientific era.

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